# The physics of black hole binaries: geodesic properties, quasinormal modes and interaction with fundamental fields

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Phys.Rev.D100(2019)no.4,044002

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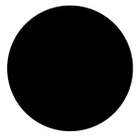
# Black hole binary

- Compared with single BH, BH binary spacetime is not deeply understood.

| Black Hole | Black Hole Binary |
| --- | --- |
| - closed null geodesic | - “Global ” closed null geodesic ? |
| - Quasi normal mode | - “Global” Quasi normal mode ? |
| - Superradiance | - Superradiance like mechanism ? |
|  |  |

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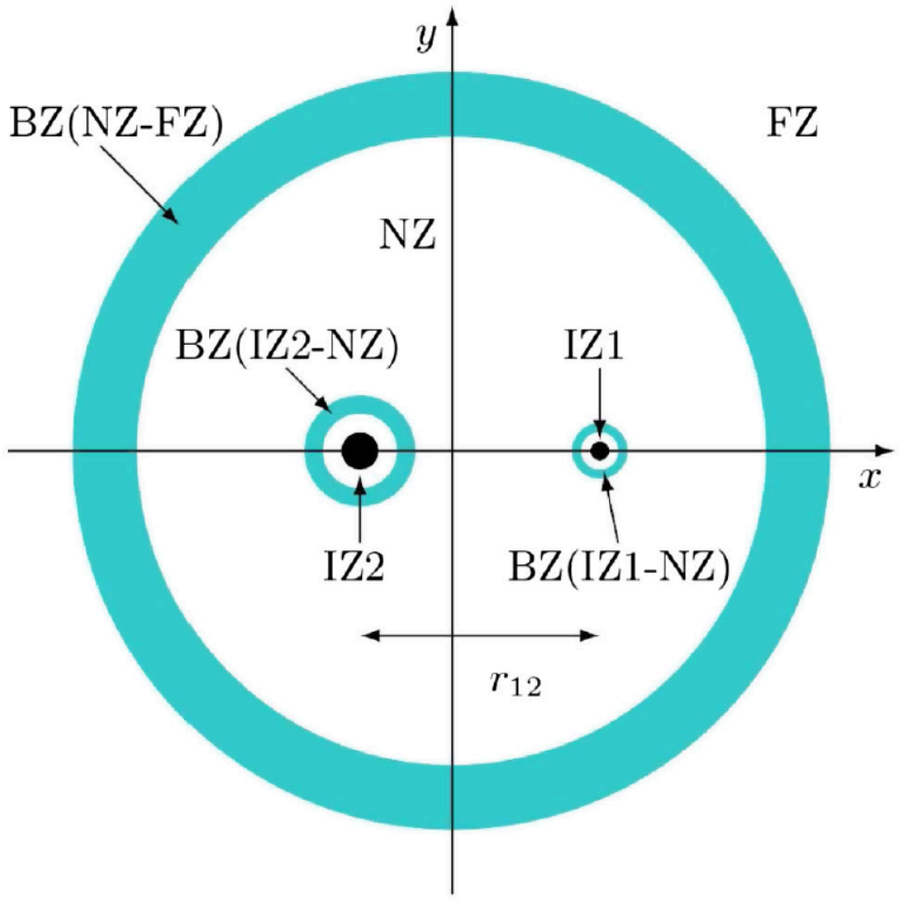
# Approximate BHB spacetime

- Long time simulation is needed.

  ➡ We use approximate BHB metic.

ref) PRD89,084008(2014)

- Construction of the metric $A = 1,2$
  - Inner Zones (IZ) : $0 < r_A \ll r_{12}$
    - a perturbed Schwarzschild BH
  - Near Zone (NZ) : $m_A \ll r_A \ll \lambda$
    - PN approximation
  - Far Zone (FZ) : $\lambda \ll r < \infty$
    - PM approximation
  - Buffer Zone (BZ)
    - Asymptotic matching




BHB spacetime (BH1, BH2)

$r_{12}$ : BH separation

$m_1 = m_2 = M/2$

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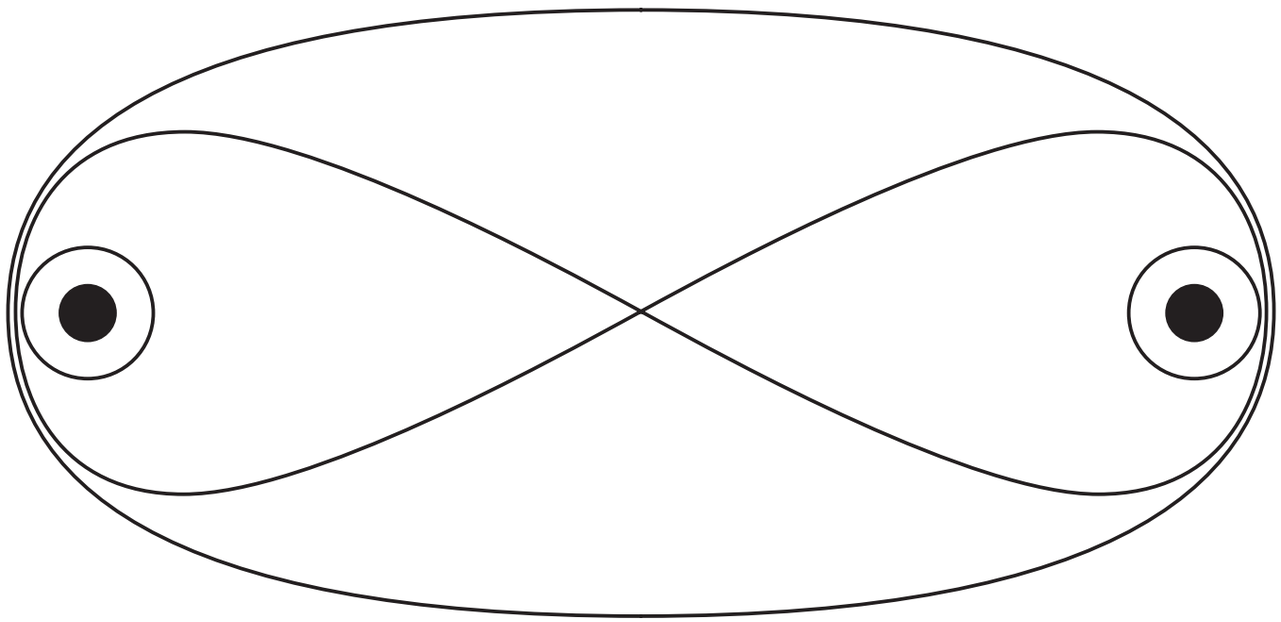
# Global closed null geodesic

- We solved null geodesic on the BHB metric.
- And, we found three types of “nearly” closed null geodesics.
  - Geodesic surrounding each BH
  - A global non-intersecting geodesic
  - An eight-shaped geodesic



a.s.c.

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# Our numerical code

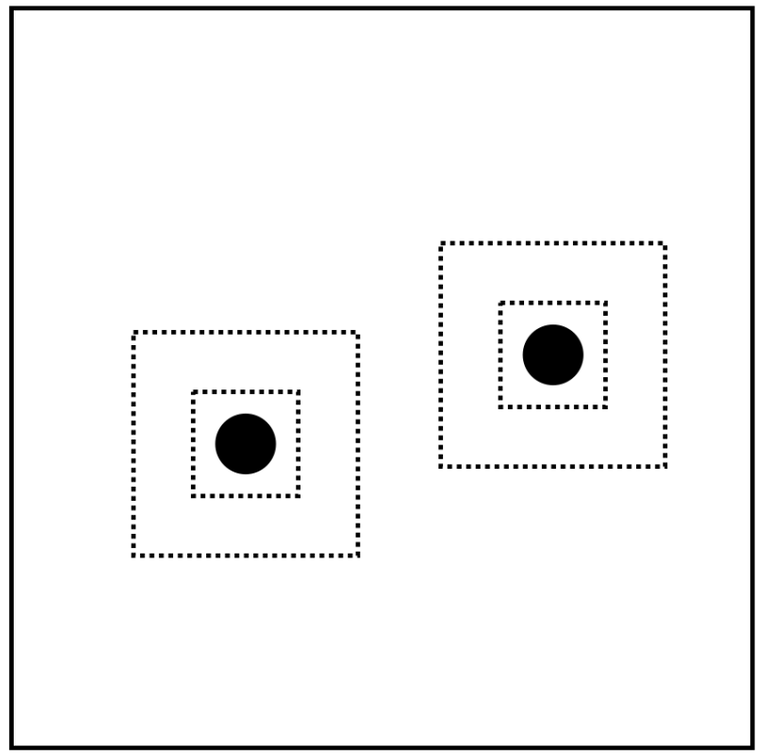
- QNM appears in late time behavior of wave equation.

➡ We solve the Klein-Gordon eq. around BHB numerically.

- We developed new thorns on EinsteinToolkit.
  - Approximate BHB background.
  - Massless scalar field on the BHB spacetime with excision.
    - $\Box\Phi = 0$
    - Ingoing spherically symmetric initial data.

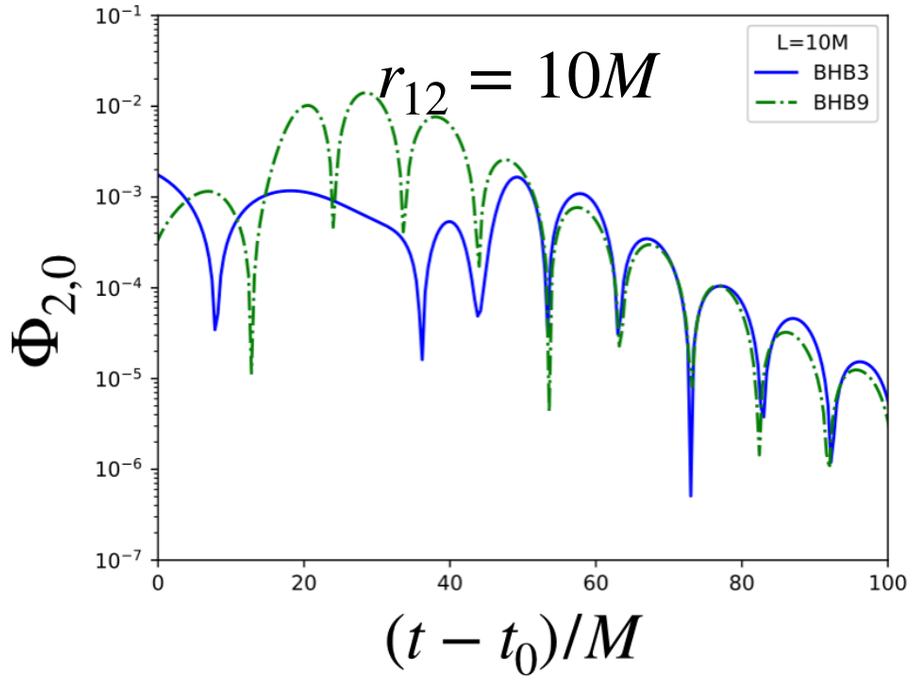
$$\begin{cases} \Phi(0,\vec{x}) \equiv \Phi_0 = \dfrac{\sin \omega r\, W(r)}{r}\, e^{-(r-r_0)^2/\sigma^2} \\ \partial_t \Phi(0,\vec{x}) = \partial_r \Phi_0 + \dfrac{\Phi_0}{r} \end{cases}$$

BBH

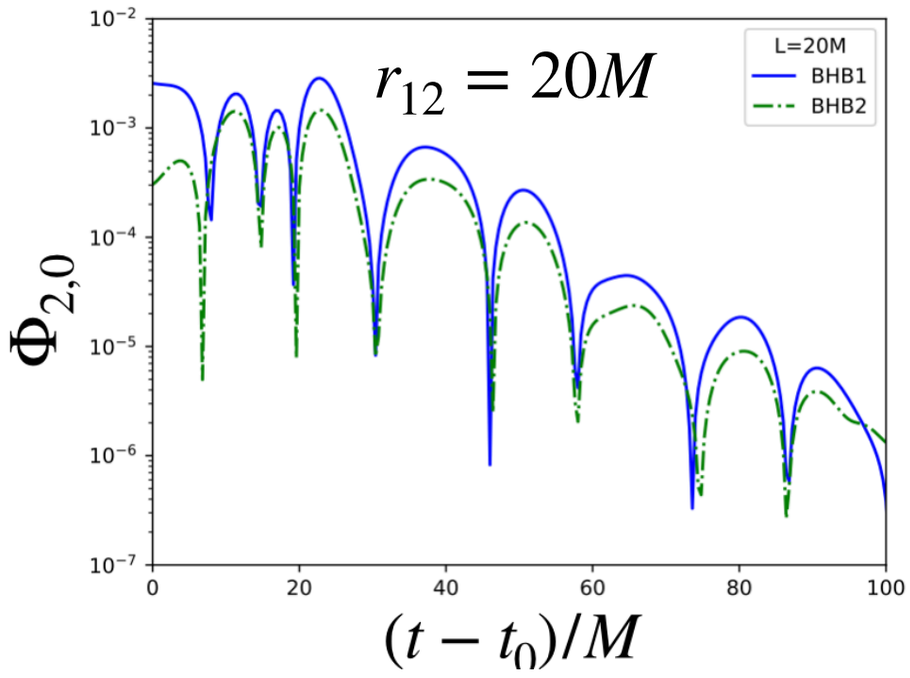


# Global QNM

- The late behavior does not depends on the initial data.




$T \simeq 18M$

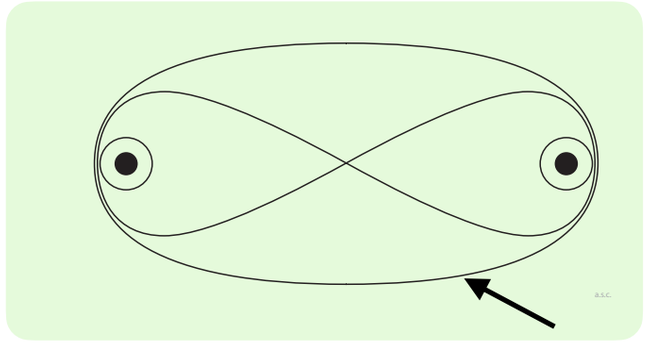



$T \simeq 28M$

- The periods of QNM are consistent with the expected period from global null closed geodesic.

$$T_{\mathrm{QNM}} \simeq L + 8M$$

➡ This is “global QNM”



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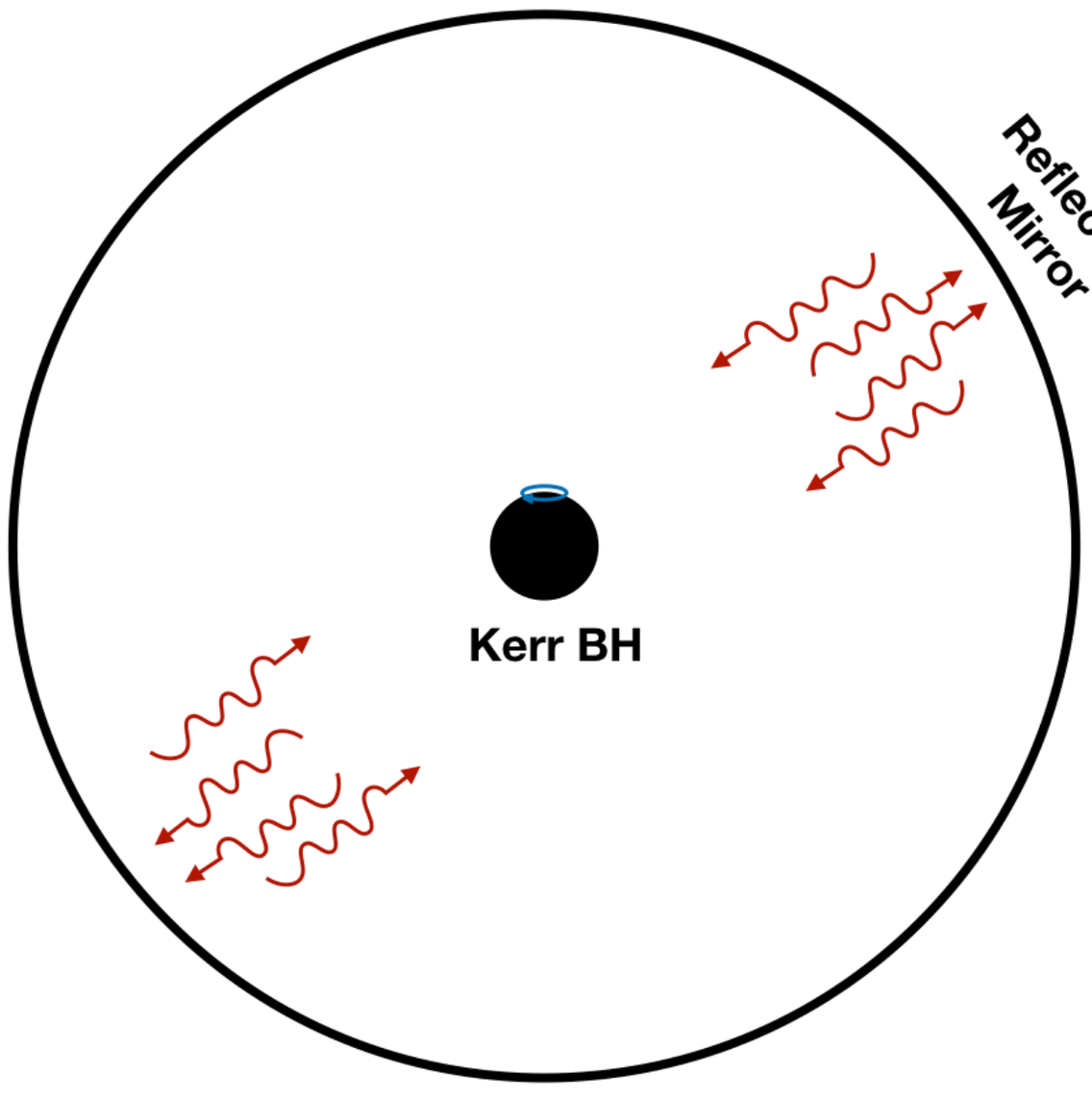
1. Introduction
2. Construction of BH binary spacetime
3. Our results
   a. global closed null geodesic
   b. global QNM
   c. superradiant like instability **(ongoing work)**
4. Summary

# Super-radiant like instability

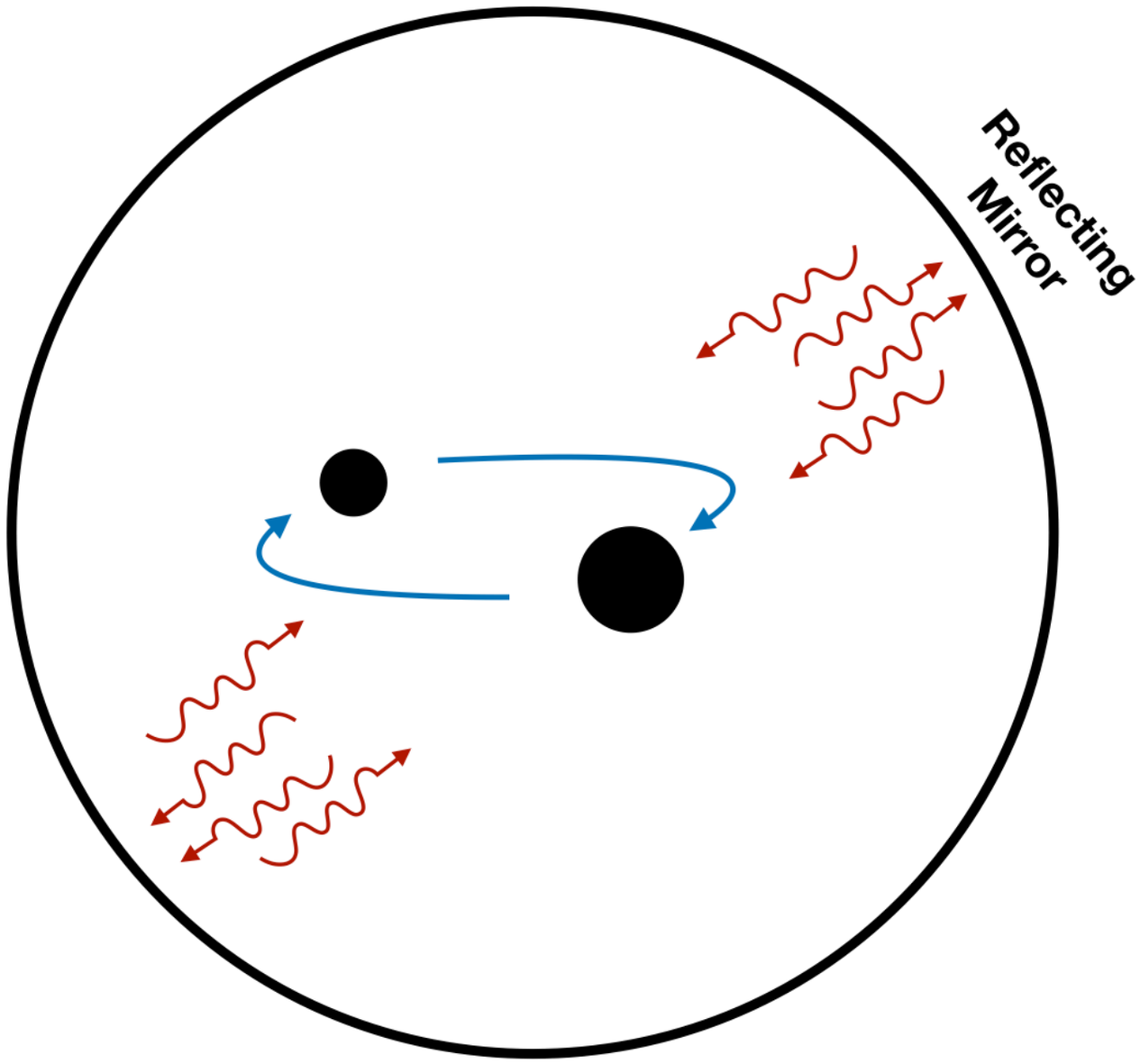
Black hole bomb

cf: super-radiant instability



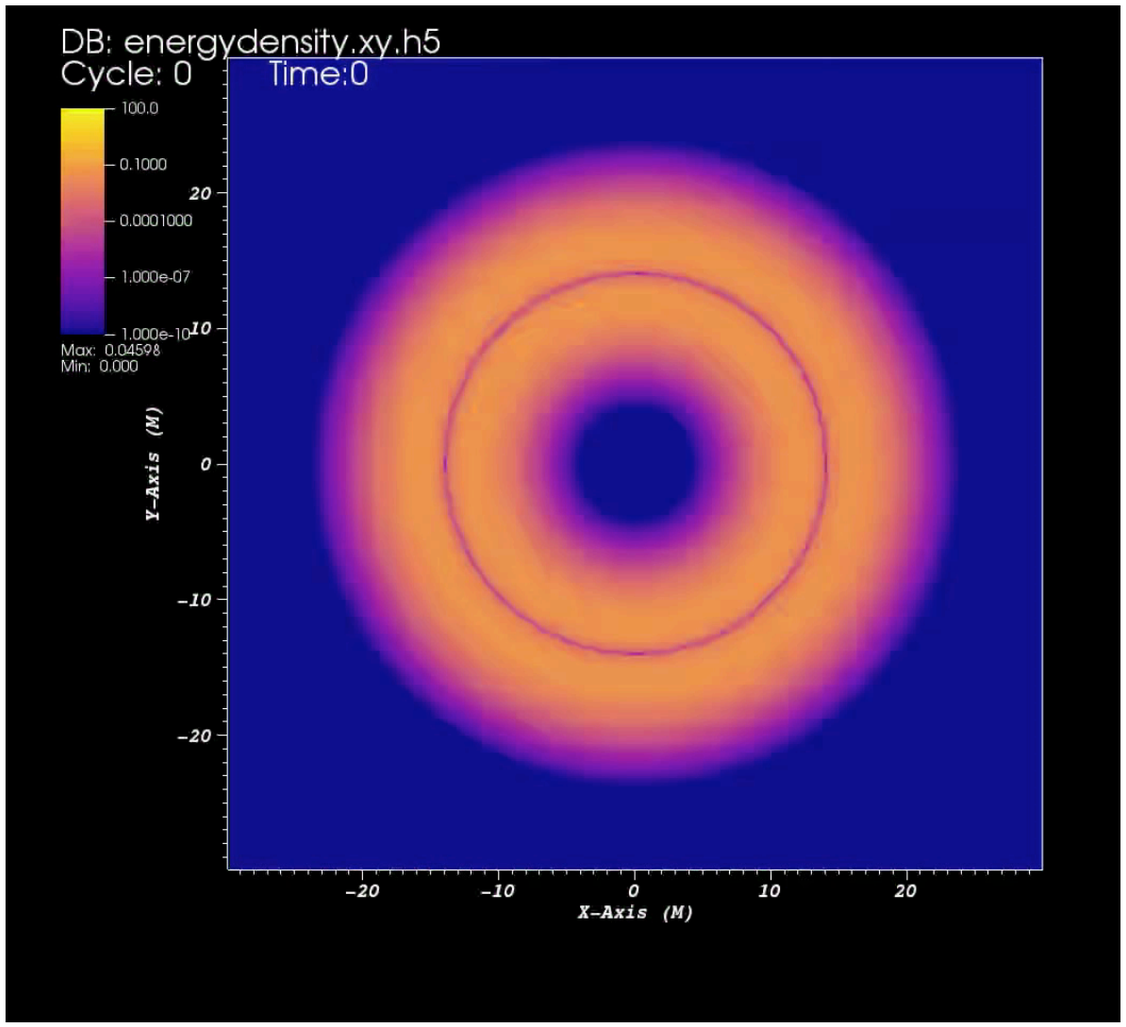
# Super-radiant like instability

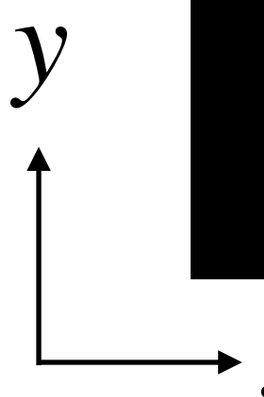
Black hole binary bomb (?)
super-radiant like instability (?)



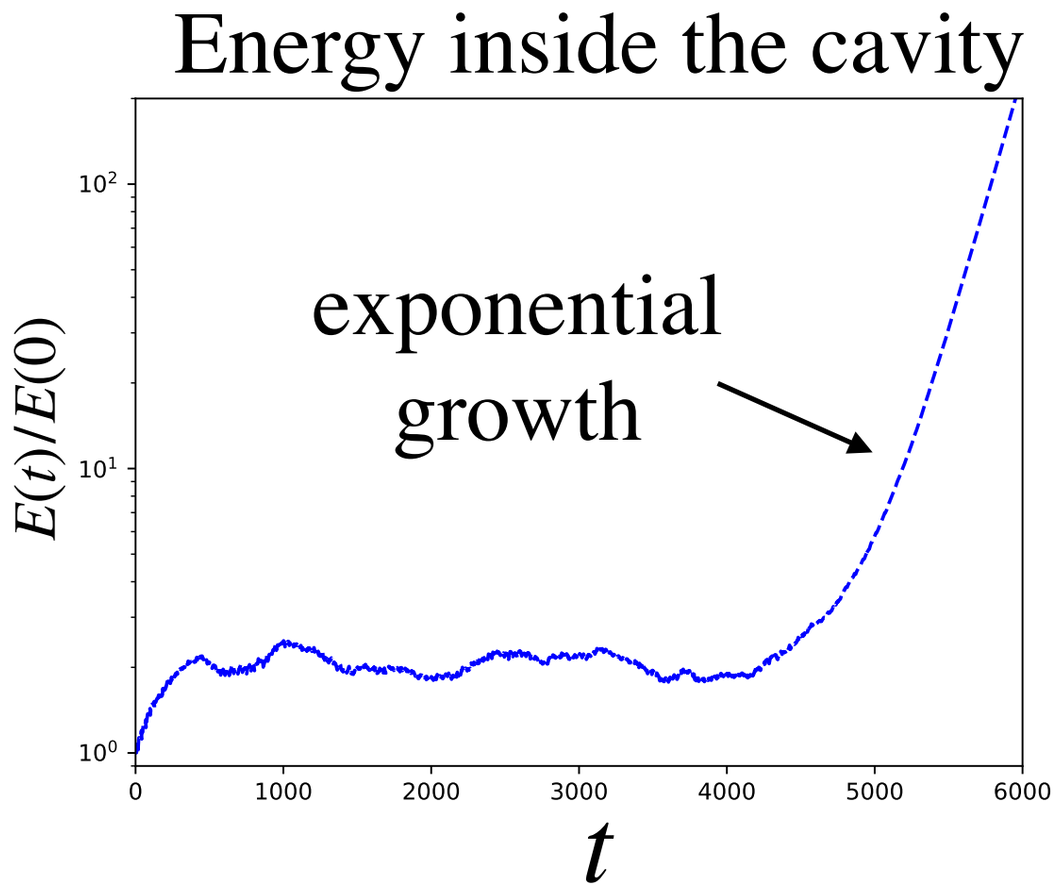
# Toy model

- Massless scalar field inside a cavity with a binary of two reflecting objects in 2+1 Minkowski



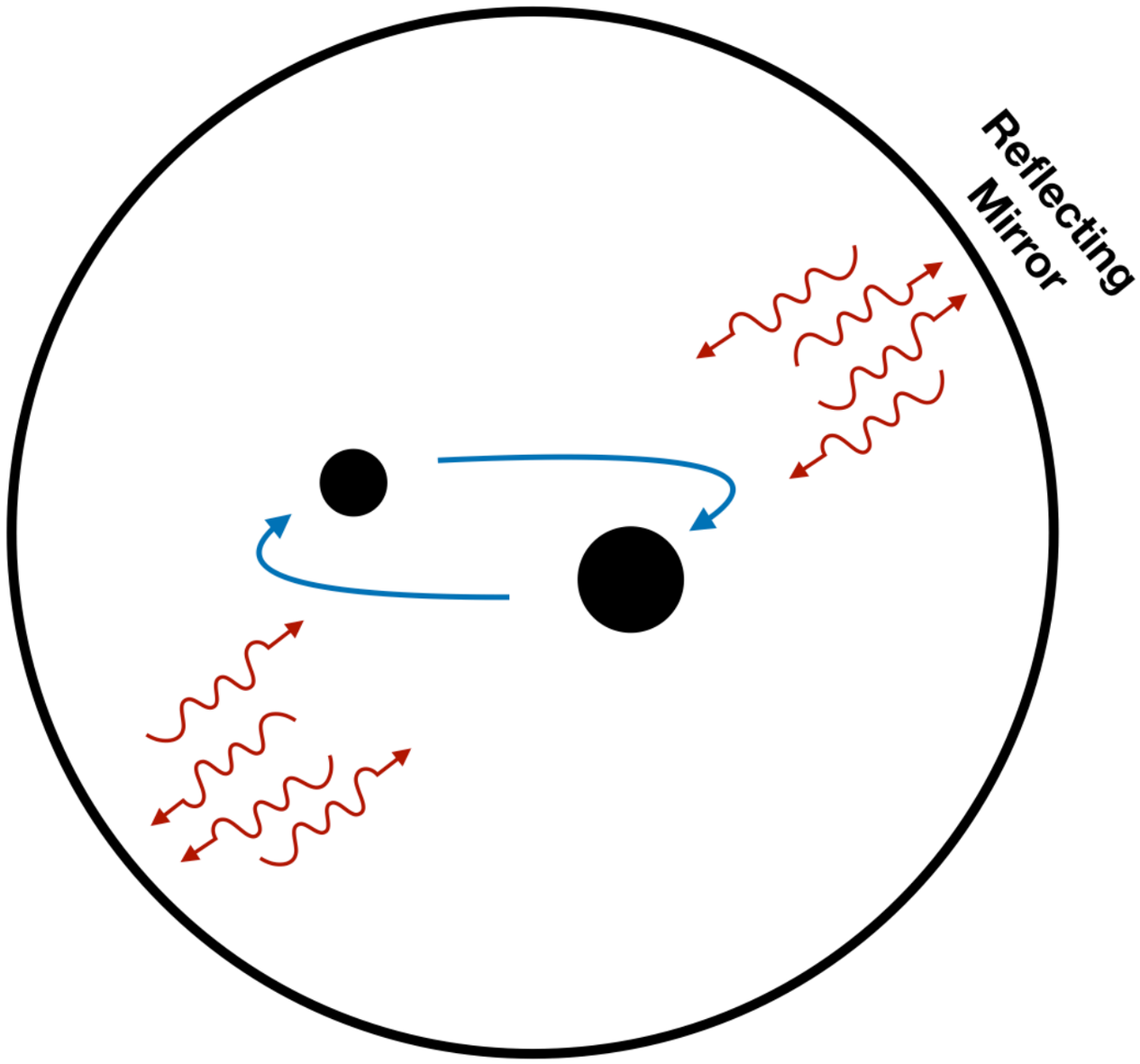




$R_{\text{ext}} = 30,\ \Omega = 0.14,\ r_{\text{b}} = 0.5$



# Super-radiant like instability

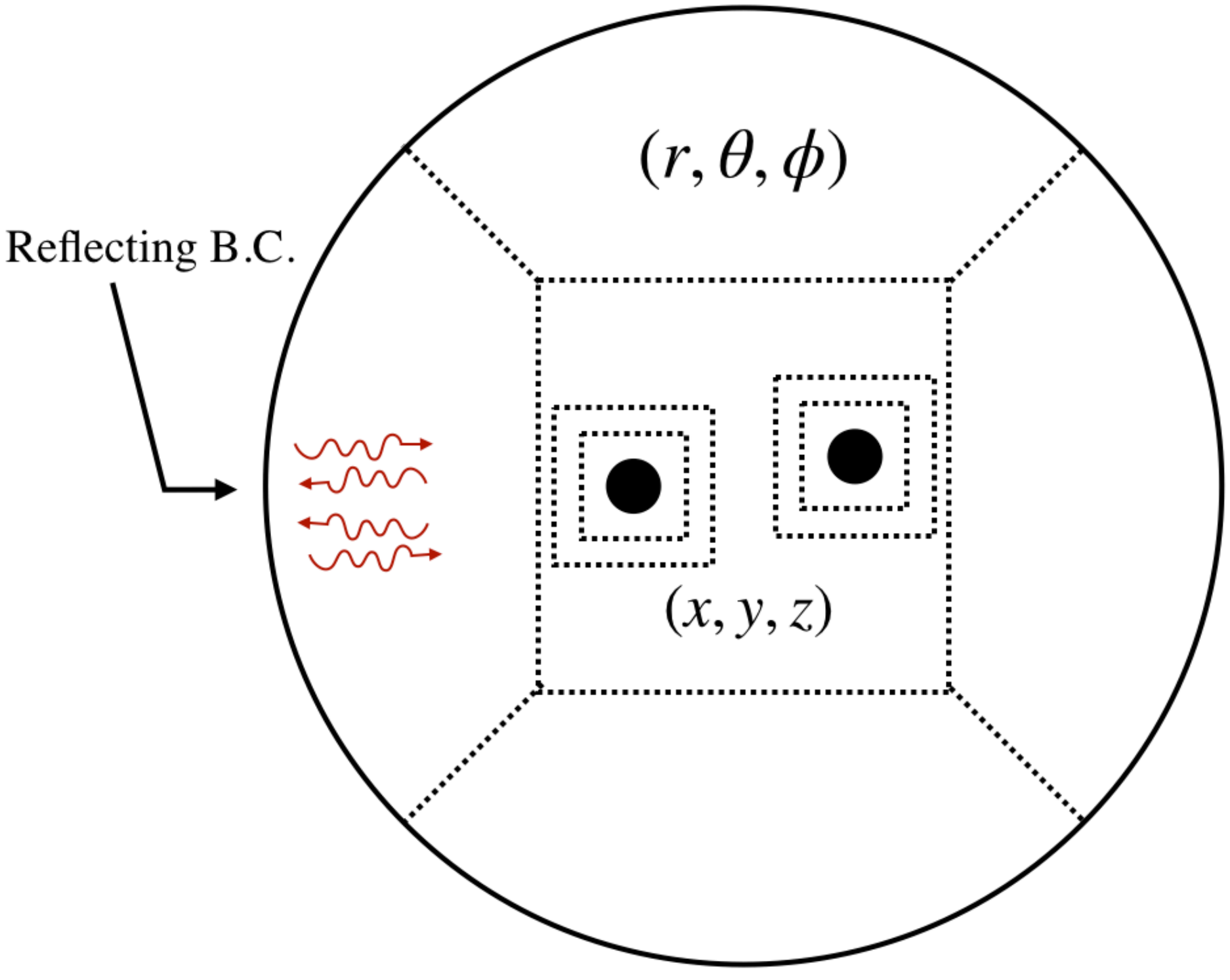
Black hole binary bomb (?)
super-radiant like instability (?)



# Our numerical code

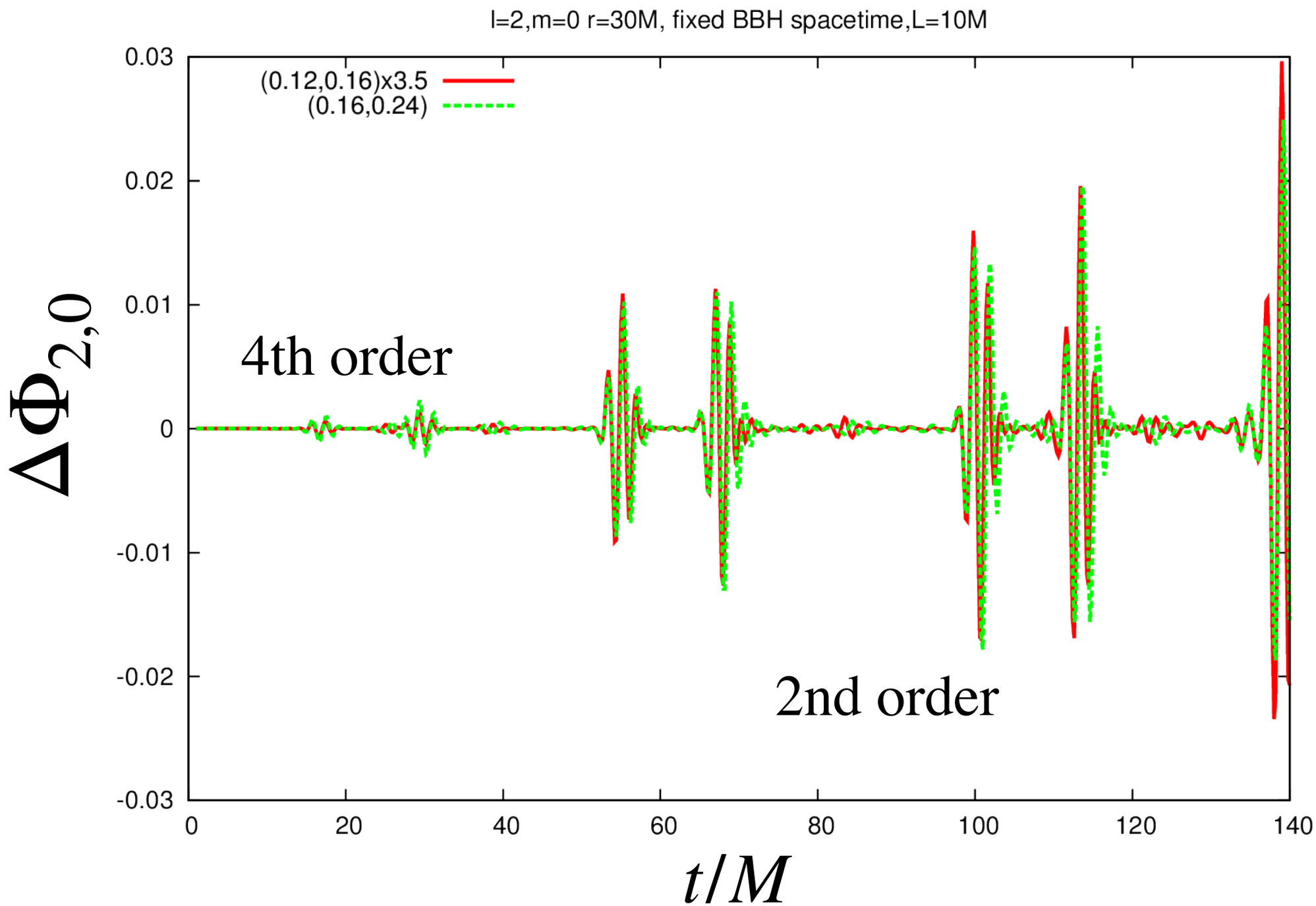
- Set up
  - Massless scalar field around BHB in cavity (3+1 dim).
- We developed our thorns on EinsteinToolkit.
  - Giving Approximate BHB background.
  - Solving massless scalar field on the BHB spacetime with excision.
    - $\Box \Phi = 0$
    - Reflecting boundary condition on the spherical boundary.
- The llama thorn gives multi-patch structure.

# Grid structure



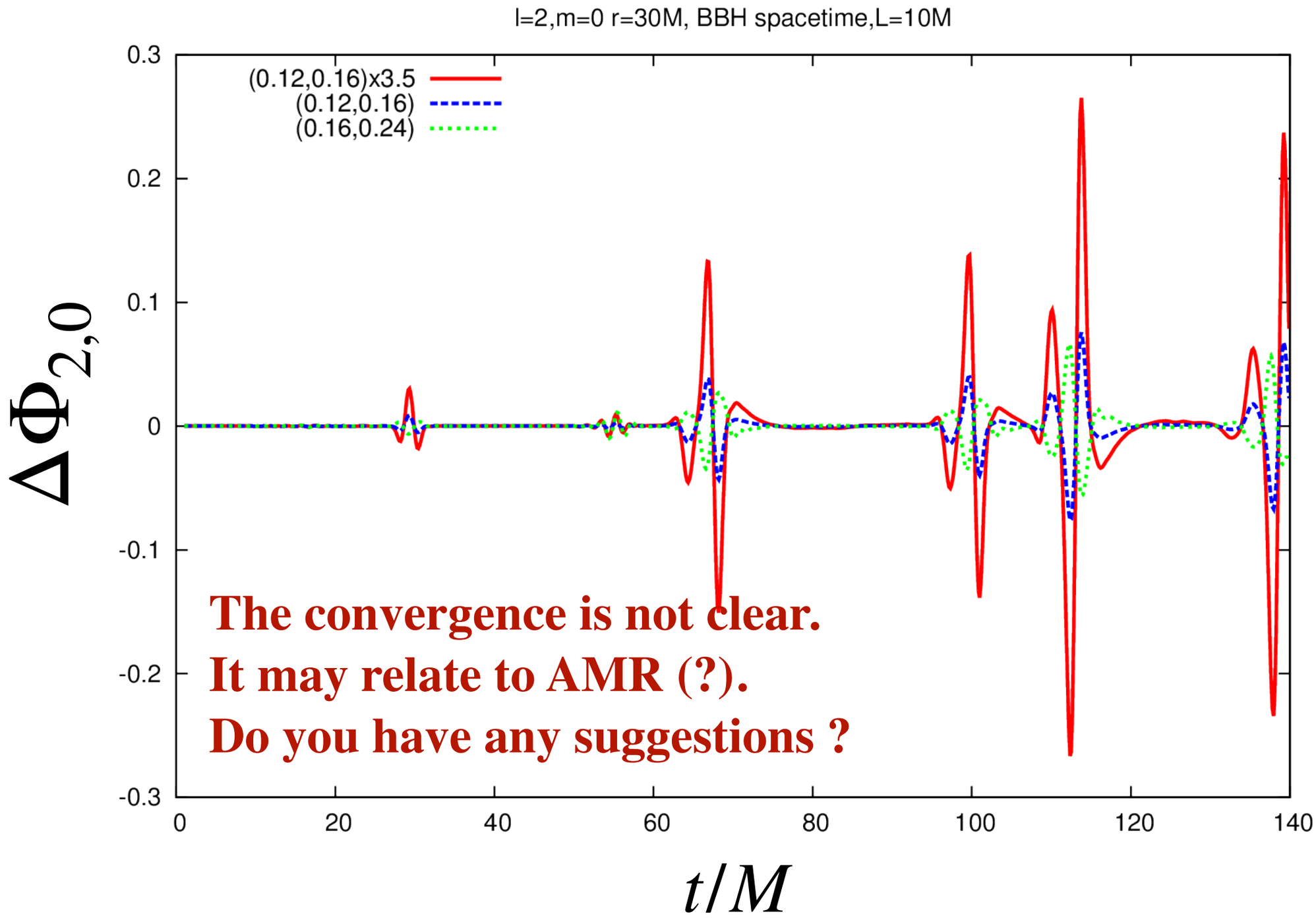
# Convergence Check

- Fixed BHs (fixed mesh refinement) ➡ **OK**

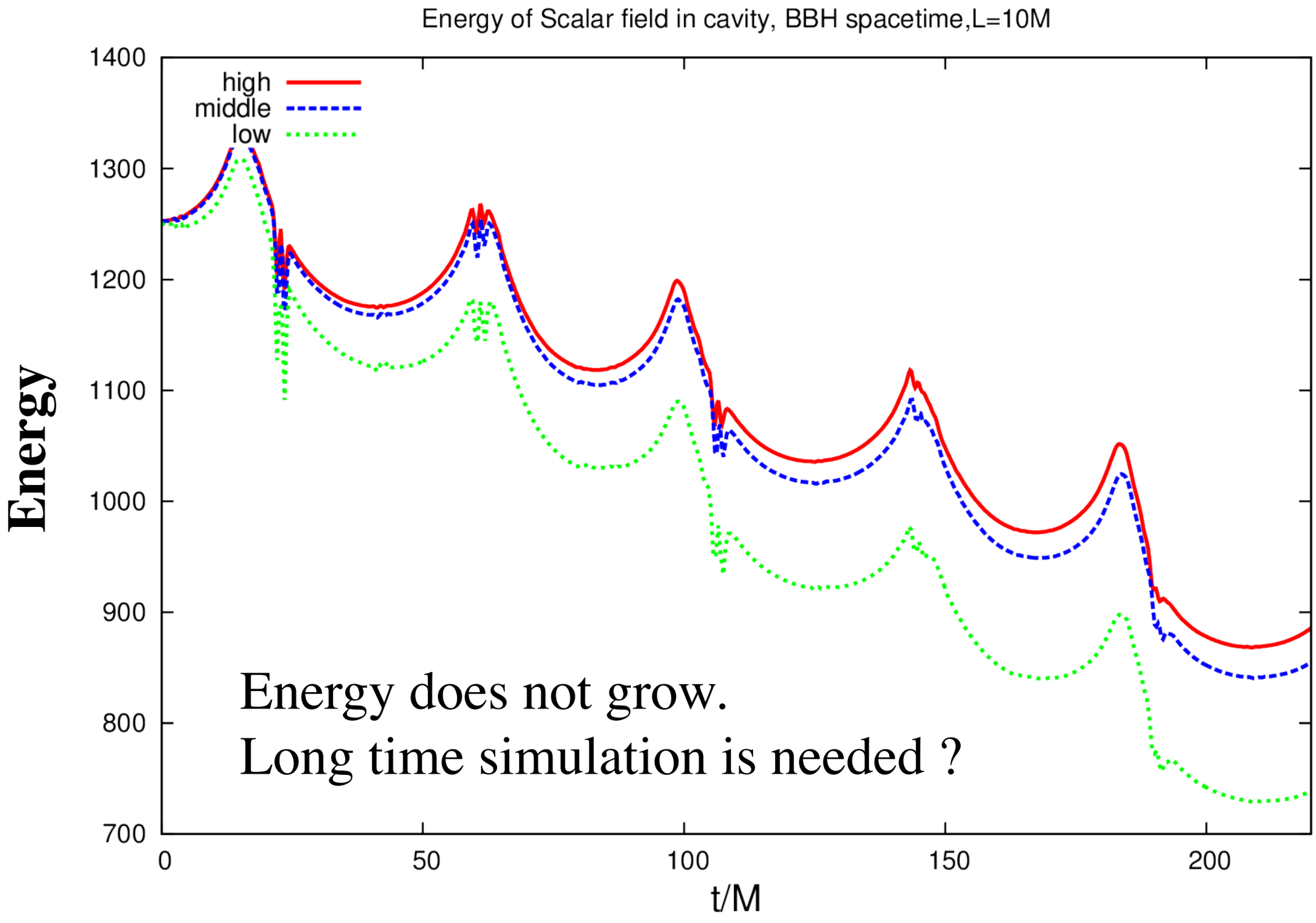


# Convergence Check

- Binary BHs (adaptive mesh refinement)



# Preliminary Result



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# Summary

- Result
  - closed null geodesic around BHB.
  - global QNM in BHB spacetime.
  - Energy extraction (in toy model)

- Ongoing work (BHB bomb)
  - We could check the numerical convergence on fixed BHs spacetime.
  - The convergence on BHB spacetime is not clear.

➡ If you have good suggestions, let me know.

**Thank you for your attention.**